Staff Paper P01-11 September 2001

STAFF PAPER SERIES

The Role of the Public Sector in Technology Development:

Generalizations from General Purpose Technologies

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Abstract:
In the new science and technology policy literature that emerged in the early 1980s it was held, while public support for science is appropriate, public support for technology development represents an unproductive use of public resources. The perspective that emerges in my recent book, *Technology, Growth and Development: An Induced Innovation Perspective* is quite different. Government has played an important role in technology development and transfer in almost every U.S. industry that has become competitive on a global scale.

The Role of the Public Sector in Technology Development:

Generalizations from General Purpose Technologies*

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* The material in this paper is drawn from Vernon W. Ruttan, *Technology, Growth and Development: An Induced Innovation Perspective* (New York: Oxford University Press, 2001). The citations in the text of this paper are referenced in the above book. Earlier drafts of this paper have been presented in seminars at the University of Minnesota (Nov. 10, 2000); Harvard University Center for International Development (Dec. 12, 2000); University of Wisconsin Department of Agricultural and Applied Economics (April 6, 2001).

INTRODUCTION

In the new science and technology policy literature that emerged in the early 1980s it was generally held, while public support for science is appropriate, that public support for technology development is an unproductive use of public resources. Skepticism of the government role in technology development was not limited to critics from the right; critics from the left increasingly share this view. This negative view was captured in the title of the book by Cohen and Noll (eds.), *The Technology Pork Barrel* (Brookings, 1991). The view that emerges from my recent book, *Technology Growth and Development* (Oxford, 2001) is quite different.

In this paper I trace the role of government in technical change in the six general purpose technologies that I studied in preparing *Technology, Growth and Development*. Government has played an important role in technology development and transfer in almost every U.S. industry that has become competitive on a global scale. Mass production was a direct outgrowth of the New England Armory System of interchangeable parts in gun production. I also draw illustrations from the agricultural, power and light, chemical, computer, and biotechnology industries. A more complete paper would draw on the role of public support in the several transportation industries.

In tracing the sources of technology development in the several general purpose technologies I find it necessary to consider the institutional innovations associated with the technology developments. I employ an induced innovation perspective in which both technical and institutional change are induced by changes (and differences) in relative resource endowments and prices (Ruttan 2001a, 100-146). I also employ a much more complex view of the relationship between advances in scientific and technical knowledge and the role of the public and private sectors in advancing scientific and technical knowledge than the simple linear model that has dominated the early post World War II science and technology policy literature (Fig. 1).

THE NEW ENGLAND ARMORY PRACTICE AND MASS PRODUCTION

Economic historians have traditionally characterized the American System as the assembly of complex products from mass-produced interchangeable individual parts (Rosenberg, 1972:87-116). The system which had gradually evolved since the 1820s first came to prominence in firearms manufacturing. In this section I trace the evolution of the system of interchangeable parts in gun production to the first mass production of automobiles by the Ford Motor Company.

The significance of interchangeability can best be understood when compared to the handicraft technology used in British gun making into the 1850s. Handicraft gun making involved precisely fitting together, primarily by hand filing and fitting, individual components produced by a large number of craftsmen. Substantial skill and patience were required for tasks such as filing and recessing the gunstock to properly accommodate the lock and barrel and correctly arranging the pins and screws. In contrast, the system of interchangeability required little skill, and thus vastly simplified gun production, repair, and maintenance. It also meant that an army in the field no longer had to be accompanied by armorers to repair a broken part or fit a new part (Mokyr, 1990:136, 137).

In the early and mid-1850s a number of industrial commissions from Great Britain and other European countries traveled to the United States to report on the machine processes used in American manufacturing and to purchase tools and equipment. "During a visit to the Army Ordnance Department armory in Springfield, Massachusetts, one such committee selected 10 muskets, each made in a different year between 1844 and 1858, "which they caused to be taken to pieces in their presence, and the parts placed in a row of boxes, mixed up together. They then requested the workman, whose duty it is to 'assemble' the arms to put them together, which he did-the Committee handing him the parts, taken at hazard-with the use of a turnscrew only, and as quickly as though they had been English muskets, whose parts had carefully been kept separated” (Rosenberg, 1972:92).

The large-scale production that would typify the American system was quite limited prior to 1840. Only the Army was in a position to subsidize the high cost of moving materials to remote manufacturing locations such as Springfield and Harpers Ferry and then shipping the finished firearms to the posts at which they were to be used. During the second half of the nineteenth century "armory practice" defused to other branches of manufacturing, usually by the movement of skilled machinists from the New England arms factories to other industries and regions.

The sewing machine industry was the first to adopt armory techniques. At the Wheeler and Wilson Manufacturing Company (Bridgeport, Connecticut), the armory system was adapted to the production of sewing machines in 1857 by former employees of the Colt and Springfield armories. In contrast, the Singer Manufacturing Company, which achieved a dominant position in the industry because of its aggressive advertising and its efficient distribution system, did not make the transition to full armory practice until it opened a new factory at Elizabethport, New Jersey, in 1873 (Hounshell 1981).

Bicycle production represented a transitional technology between the American system that emerged out of New England Armory Practice. It was responsible for a number of technical innovations, including ball bearing, steel sheet stamping and rubber tires. The American system of mass production emerged in its most highly developed form at the Ford Motor Company in the first decade of the twentieth century. In 1909, a Model T emerged from Ford's Highland Park factory every forty seconds of the working day. (Hounschell, 1984: 248). "In Mass production there are no fitters" (Ford 1926: 822). The initial effect of the assembly line was to enhance efficiency. Its long-term effect, though, has been to deprive American mass production industry of the creative contributions "of the learning by doing"--of the machine operators and mechanics, the very workers whose creativity gave rise to the New England Armory system.[1]

AGRICULTURAL RESEARCH

The institutional pattern that emerged for the organization of U.S. agricultural research drew heavily on the German system for its model of institutional organization and in its training of young scientists. A number of the "science entrepreneurs" who were responsible for the establishment of U.S. agricultural research stations had studied in Germany. Institutionalization of agricultural research in the United States involved the creation of a dual federal-state system. The federal system developed more rapidly than the state system. Yet it was not until the closing years of the nineteenth century that either the state or the federal system acquired any significant capacity to respond to the rising demand for scientific and technical knowledge.[2]

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[1] The New England Armory System of the mid-1800s also induced a number of institutional changes in the management of men and machines. The inside contract system was one of the early managerial innovations associated with the American System. An early example was the arrangement for production of gunstocks at the Springfield armory. In 1819 Thomas Blanchard invented the first lathe that could reproduce the irregular shape of a gunstock (or any other irregularly shaped wooden object such as an ax handle or a shoe last). The Springfield armory agreed to provide Blanchard with shop space, free use of materials and machinery, waterpower, and the necessary raw materials for producing gunstocks. Blanchard contributed the use of his patented machinery and received a contract price of 37 cents per gunstock (Hounshell, 1984:38).

[2] The key federal legislation establishing the USDA-SAES research-teaching-extension system included the act establishing the USDA, the Morrill or Land-Grant College Act of 1862, the Hatch Act, providing for state agricultural experimentation research support in 1887, and the Smith-Lever Act, providing federal support for the

It was not until, toward the end of the century, that a viable pattern of organization for agricultural research in the federal Department of Agriculture emerged. It involved breaking away from a discipline-oriented structure and organizing scientific bureaus focusing on a particular set of problems or commodities such as the Bureau of Plant Industry, the Bureau of Entomology, the Bureau of Soils, the Bureau of Biological Survey, and the Weather Bureau (Dupree, 1957:165; Huffman and Evenson, 1993:31-34). The capacity of the state Land-Grant (public) universities to provide new scientific and technical knowledge of agricultural development lagged that of the Department of Agriculture until well into the 20th century. The first state experiment station, the Connecticut State Agricultural Experiment Station, was not established until 1877. But it was not until the early 1920s that it was possible to claim, with some degree of confidence, that a national agricultural research and extension system had been effectively institutionalized at both the federal and state levels.[3]

Since the mid-1960s, the federal-state agricultural research system has undergone a series of external and internal challenges from a variety of scientific, populist, and ideological perspectives. The external challenges included populist criticisms of the narrow focus of agricultural research, typified by two seminal publications: Rachel Carson's *Silent Spring* (1962) and Jim Hightower's Hard *Tomatoes, Hard Times* (1973). Carson's book drew attention to the environmental effects of intensive use of agricultural pesticides. Hightower's book criticized the

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state agricultural extension program in 1914. Huffman and Evenson (1993:3) note: "The institutions, as embodied in these legislative acts, were not simply the product of exceptional 'inspiration' . . . of legislators and policy makers of the day. By the time each of these major pieces of legislation was passed considerable institutional development and experience with earlier institutions had been realized."

[3] In the United States between two-thirds and three-fourths of public sector agricultural research has traditionally been conducted at the state agricultural experiment stations operated by the state Land Grant universities. In other OECD countries, less than one-fourth of public agricultural research has been conducted at universities (Alston et al., 1998, Table 2). In the Japanese system a relative high percentage of agricultural research is funded by prefecturial governments and conducted at prefecturial experiment stations. Hayami and Ruttan have argued that the decentralized funding and governance of agricultural research in the United States and Japan has made public sector agricultural research in the two countries particularly responsive to market forces and the needs of farmers in each state or prefecture (Hayami and Ruttan, 1985:251).

public agricultural research system for subverting the interests of farmers and consumers in favor of agricultural business interests. Although both books contained a frustrating mélange of errors and half-truths, along with valid criticisms, they did serve to dramatize the major limitation of the U.S. agricultural research system-that it was more narrowly focused on plants, animals, and soils rather than farmers and communities (Fitzgerald, 1991).

A second, and opposing criticism emerged from within the agricultural research community itself. In 1972 a committee of the National Research Council severely criticized the quality of research being conducted by the USDA and the state agricultural experiment stations as outmoded, pedestrian, and inefficient (National Research Council, 1972). It was also critical of the formula-funding mechanism the federal government used to support state agricultural research and the limited role of peer evaluation in the allocation of research resources. While the populists were criticizing agricultural research for its narrow focus on productivity-enhancing technical change, the internal criticism objected to excessive focus on technology development and the neglect of basic science. An important consequence of the internal criticism was the passage of the legislation in 1977, which authorized a USDA competitive research program for plant science and for nutrition research that would be open to all scientists in either public or private institutions.

While attempting to respond to these external and internal criticisms, both the federal and state systems have been subject to substantial budget stringency. Between 1890 and 1980, resources available to the U.S. public agricultural research system had grown at a real rate of over 4% per year. Since 1980 the resources available to the federal system have remained essentially unchanged in real terms while support at the state level has grown more slowly than in the past. Meanwhile private agricultural research has continued to grow rapidly (Huffman and

Evenson, 1993:95, 96; Fuglie et al., 1996:9-18). By the early 1970s expenditures for private sector agricultural research began to exceed the level for public sector agricultural research. In 1996 USDA research expenditures were $936 million, SAES expenditures were approximately $2.2 billion, and private sector expenditures were approximately $3.9 billion (Figure 6.6). As private sector agricultural research has grown there has also been a shift in its composition. Research on post harvest technology has risen relative to production-oriented research. And within production-oriented research the share directed to research on mechanical technology has declined while the share directed to advancing biological and chemical technology has risen. Public sector agricultural research is concentrated even more heavily than private sector agricultural research on advancing biological technology (Huffman and Evenson, 1993:93-127).[4]

The first economic studies of rates of return to agricultural research were the studies initiated by T. W. Schultz and Zvi Griliches at the University of Chicago in the 1950s. The Griliches study indicated social rates of return in the range of 35-40 percent. Subsequent assessment studies suggest continued social rates of return that are high by any standard (Huffman and Evenson, 1993; Pardey and Alston, 2000). These high rates of return appear to carry little conviction on the part of state and federal legislators in a political environment that questions the role of public resources for technology development. The effect has been to precipitate a frantic search for private funding (Rausser 1999).

THE CHEMICAL INDUSTRY

Governments have played a particularly important role in the development and diffusion of the chemical industry. Germany was the first nation to adopt a policy of deliberately encouraging

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[4] For a comparison with recent trends in other developed countries see Alston, Pardey, and Smith (1998d).

science and technology as a stimulus to industrialization. The chemical industry was viewed as of strategic importance both economically and militarily. It was the means whereby Germany hoped to overcome resource limitations. Investment in the training of large numbers of scientists and the establishment of new scientific institutions led directly to Germany's domination of the world chemical market by the end of the nineteenth century. The U.S. government played an active role after both World War I and World War II in the transfer of German scientific and technical capacity to the United States (Spitz, 1988; Borkin, 1978).

The Haber-Bosch Process

The close linkages between the public and private sector in industrial research in Germany is illustrated by collaboration between Haber and Bosch in the development of synthetic nitrogen. German growth in interest in the development of synthetic nitrogen was induced by the rapid demand for nitrogen fertilizer, which, by the early 1900s, appeared to be rapidly outrunning the supply of Chilean sodium nitrate. By 1909 the German physical chemist, Fritz Haber had developed a process of directly synthesizing ammonia from hydrogen and nitrogen and had established the optimum conditions for the large-scale synthesis of ammonia. Commercial development was undertaken by a team of mechanical engineers, lead by Carl Bosch, of the Badische Anilin and Soda-Fabrik (BASF). The first successful direct synthesis of ammonia on a commercial scale was carried out by BASF in 1913. Bosch rose to head BASF and led the effort to cartelize the German chemical industry.

The Haber-Bosch process was clearly induced by resource limitations (Hohenberg, 1967:44). It was "a supreme instance of a country developing a new technology that enabled it to overcome the shortage of a critical input-chemically bound nitrogen" (Landau and Rosenberg, 1992:96). The development of synthetic nitrogen had implications for other industries. It initiated technical developments that led to a long term continuing decline in the price of nitrogen fertilizer, which, in turn, induced geneticists and plant breeders to develop higher yielding fertilizer-responsive crop varieties.

The relationship between Haber and Bosch illustrates the close relationship among science, industry, and government that has characterized advances in chemistry and in chemical engineering. Haber was a strong advocate of such collaboration both in his early work and later as Director of the Kaiser Wilhelm Institute for Physical Chemistry in Berlin. Haber was also a committed German nationalist. During World War I he headed the chemistry section in the War Department for Raw Materials. In that capacity he supervised the development and first use of chlorine gas in chemical warfare. Haber received the Nobel Prize for Chemistry in 1918 for the research that led to the development of the Haber-Bosch process. Bosch received a Nobel Prize in 1931 jointly with Frederich Bergius for his research on high-pressure chemical processes.[5]

Chemical Engineering

The emergence of chemical engineering as a separate discipline was a distinctly American phenomenon in which a single public university, the Massachusetts Institute of Technology (MIT), played a dominant role. In the later part of the nineteenth century, as noted earlier, Germany had established a tradition of chemical research with strong linkages between academic research and industrial technology development. In Germany separate roles were maintained, however, for the chemist and the engineer. In the United States concerns about the role and

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[5] Haber was forced to resign his post and fled Germany as a result of the anti-Semitic policy of the Hitler regime. For further discussion of the contribution of the German chemical industry to the German military capacity, see Grant et al. (1988:34-36) and Borkin (1978).

status of the chemical engineer, as distinct from the role of analytical chemists and mechanical engineers, contributed to the formation of a separate professional identity for chemists employed as plant superintendents and managers and in chemical plant design and construction (Reynolds, 1991:343-365).

The first curriculum with the title of Chemical Engineering was organized by Professor Lewis Norton at MIT in 1888 (Houghton, 1972; Servos, 1980). In 1905, Professor William H. Walker, professor of industrial chemistry, and Arthur H. Noyes, professor of physical chemistry, collaborated to reorganize the program in industrial chemistry from Norton's heterogeneous collection of courses in chemistry and mechanical engineering into a more integrated program of study. By 1915 the central integrating concept had become the study of unit operations first developed by Arthur D. Little in his consulting practice.

“The central idea was to reduce the vast number of industrial chemical processes into a few basic steps such as distillation, absorption, heat transfer, filtration, evaporation, reaction and the like. Walker and Little were developing their own scientific analysis of the principles of chemical engineering based on unit operations ... (that) involved new conceptual frameworks not used or needed by chemists ... because chemists did not concern themselves with how one designs industrial size plants and equipment” (Landau and Rosenberg, 1992:88).

In 1916 MIT established a free-standing School of Chemical Engineering Practice, an industry-academic cooperative master's course taught at an advanced applied level. An autonomous Department of Chemical Engineering, separate from both the Chemistry Department and the School of Chemical Engineering Practice, was established in 1921.

Technology Transfer

The development of the U.S. chemical industry was substantially advanced by military support for the transfer of German knowledge, capacity and personnel to the U.S. after World War I and World War II. Dupont represents an example of the effect of such transfers. For nearly all of its first 100 years, prior to the 1920, Dupont was solely a manufacturer of explosives and related products. Shortly after the turn of the century it began diversifying into various fields not directly related to explosives; and by the early 1920's was making great strides toward becoming a diversified chemical company (Mueller, 1962: 323-24).

Even as late as the early 1950's, however, Dupont's growth was largely based on products developed by others and introduced into the American market by Dupont. This included viscose rayon, tetraethyl lead, cellophane, synthetic ammonia, acetate rayon, freon, polyethylene, and titanium pigments and metal. It had been more successful in making process and product improvements than in the chemical discovery and product development. Dupont did not become big by investing in research. It began investing in research because it was big!

The U.S. government played an important role in the acquisition of German patents and technical know-how by U.S. firms during and after both World War I and World War II. American firms began to acquire limited access to German chemical technology through cartel arrangements with I.G. Farben prior to World War I and through patents vested with the Alien Property Custodian during World War I. Companies such as Dupont and Dow did not have the capacity, however, to effectively exploit the patents. After World War I the U.S. Army of Occupation in Germany, at the request of Dupont, facilitated the transfer of technical documents and personnel from Germany to the United States (Borken, 1978: 38-40).

The U.S. government acted even more aggressively during and after World War II to obtain access to German chemical technology (Spitz, 1988: 1-62). At the start of the war the U.S. government confiscated the I.G. Farben operations in the United States. They were later reorganized as a U.S. company, General Aniline and Film. As the war was ending, U.S. chemical companies prevailed on the U.S. army to organize a number of teams of experienced chemical engineers and executives, some still in uniform, to prepare detailed reports on the organization and technology of the German chemical industry. The reports filed by the teams were immensely useful as a source of information on chemical technology processes and products, particularly in the area catalytic improvements.[6] In an effort to weaken the competitive position of the post World War II German chemical industry I.G. Farber was broken into three major successor companies-BASF, Hoechst, Bayer-and several smaller firms. By the late 1990's these were the three largest international chemical firms (Table 8.2).

THE COMPUTER INDUSTRY

The computer, semiconductor, and software industries were initially strongly nourished by the U.S. military and space programs. Much of the early exploratory research on computers was conducted by university-based researchers operating under government contract. Although the initial research on semiconductors was financed by the private sector, government procurement for military and space applications accounted for a high percentage of sales over the first decade of the industry's development. The research and development that led to the Internet were supported by the Defense Advanced Research Project Agency (DARPA) as a way for its contractors to more effectively communicate with each other. Even after commercial markets

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[6] These efforts have been referred to as "intellectual reparations" (Gimbel 1990). Stokes (1996) has argued that these technology transfer efforts were neither as useful as U.S. (and other Allied powers) anticipated nor as devastating as the Germans feared.

became well established substantial public resources continued to be allocated to research and education in support of the computer industry.

Electronic Digital Computers

The development of the first all-purpose, electronic digital computer, by John W. Mauchly and J. Prosper Eckert and associates at the University of Pennsylvania's Moore School of Electrical Engineering, was funded by the Aberdeen Ballistics Research Laboratory. [7] The Army was interested in a computer that could reduce the enormous labor involved in calculating artillery firing tables. The Mauchly-Eckert machine, called the Electronic Numerical Integrator and Calculator (ENIAC), completed in 1946, was capable of computing more than 1000 times faster than the Aiken electromechanical machine that had been developed at MIT. The successful completion of the ENIAC, by stimulating further military demand, provided a great impetus for the development of the computer industry, even though the original version had no immediate commercial applications.

A second project developed by the Moore School group, the Electronic Discrete Variable Computer (EDVAC), had an even more important impact on future computer development. It incorporated the concept of a stored program and sequential processing developed by Mauchly, Eckert, and Goldstine of the Moore group and the mathematician John von Neumann of Princeton University's Institute for Advanced Study (Princeton, NJ). In what came to be referred to as the von Neumann architecture, the processing unit of the computer

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[7] The electronic digital computer was conceived by John V. Atanasoff of Iowa State University in 1937. In December 1940 he demonstrated a small prototype and in 1941 he published a paper on the theory and design. In 1941 Mauchly visited Iowa State University to examine the computer, read the technical papers, and discuss his work with Atanasoff. Iowa State failed to patent the Atanasoff design. Although the issue remains controversial, most historians of computing now credit Atanasoff rather than Mauchly and Eckert as the inventor of the *electronic digital* computer (Shurkin, 1984:114-116).

fetches instructions from a central memory that stores both data and programs, operates on the data (for example, adds or subtracts), and returns the results to the central memory. Every computer system developed since the late 1940s has continued to be based on the von Neumann architecture in which both instructions and data reside in a common memory.

During and after World War II other units of the military such as the Office of Naval Research, the National Bureau of Standards, the Bureau of Census, and the National Advisory Committee for Aeronautics, were active in mobilizing resources to improve computational capabilities. Several universities initiated programs to develop stored program machines [for example, the University of California-Berkeley (CALDIC), the University of Illinois (ILLIAC), and the University of Michigan (MIDIAC)]. Although the cadre of people working on computer development came from universities, government departments, and industry, funding came almost entirely from the federal government (Flamm, 1988).[8]

Commercial Development

In the postwar period there was a rapid formation and consolidation of firms formed to exploit the new technology. Eckert and Mauchly formed the Electric Control Company in June 1946 and the Eckert-Mauchly Computer Corporation in 1947. Because they had difficulty raising sufficient capital to complete their development work, Eckert and Mauchly accepted an offer to be acquired by Remington Rand in 1950. They brought with them several contracts, including one with the Bureau of the Census to develop an EDVAC-type computer called UNIVAC.

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[8] In spite of the apparent openness of communication in the early years of computer development, bitter tensions arose over priority in invention and intellectual property rights. Much of the controversy centers on von Neumann's June 30, 1945 memorandum, "First Draft of a Report to the EDVAC," which had the effect of weakening the attempts by Eckert and Mauchly to maintain intellectual property rights in later litigation. In 1946 Eckert and Mauchly became involved in a dispute over patent fights with the administration at the University of Pennsylvania and were forced to resign. For a highly personal account of these and related controversies, see Shurkin (1984).

Personnel from the Naval Communications Supplementary Activity, who had been involved in developing computers in support of the Navy's work in cryptology, formed Engineering Research Associates (ERA) in St. Paul, Minnesota in 1946. ERA also ran into financial difficulties and agreed to be acquired by Remington Rand in 1952. With its Eckert-Mauchly and ERA operations, Remington Rand controlled a significant fraction of the total computer engineering capacity in the United States (Tomash and Cohen, 1979).

Both Eckert-Mauchly and the ERA group were disappointed by Remington Rand's lack of enthusiasm for commercial computer development. This lack of enthusiasm was shared by other office equipment firms. In 1950 IBM president Thomas Watson Sr. asserted that the one Selective Sequence Electronic Calculator (SSEC) developed by IBM and on display at the IBM headquarters in New York City was sufficient to "solve all the important scientific problems in the world involving scientific calculations" (Katz and Phillips, 1982:171). And he saw only limited commercial possibilities for computers.

Government contracts played a critical role in the development of IBM's capacity to market a fully transistorized commercial computer, the IBM 7090 (Usselman, 1993). In the early 1950s IBM became involved in a U.S.-Canadian cooperative effort to build a computerized air defense system, the Semi-Automatic Ground Environment (SAGE). SAGE was designed to detect alien aircraft, select appropriate interceptor aircraft, and determine antiaircraft missile trajectories. The system had to store and process large amounts of information and coordinate several computers in real-time mode. The success of the SAGE project led to a number of important developments that resulted in lower costs and improved performance.[9]

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[9] The SAGE project has been characterized as one of the major learning experiences in technological history (Hughes, 1998:15-67). The innovations made in connection with the SAGE project at IBM and MIT included (1) techniques to manufacture ferrite core memory rapidly, inexpensively, and reliably, (2) computer-to-computer telecommunications, (3) real-time simultaneous use by many operators, (4) key board terminals for man-machine

In 1952 the Justice Department filed an antitrust suit against IBM over its policy of only leasing its tabulating machines, monopolization of the punch card market, and price discrimination in punch card sales. But government policy, by also supporting IBM research and development, was operating at cross purposes. In 1956 IBM agreed to a consent decree resolving the antitrust suit. The IBM strategy was to forego dominance in the mature tabulating equipment and card markets and pursue dominance in the computer market. The contracts with the Air Force and Atomic Energy Commission contributed substantially to the realization of the IBM strategy (Jorgensen, 1996).

The research that lead to the development of transistors and semiconductors was initially financed and conducted at Bell Laboratories in an effort to find an alternative to vacuum tubes. The first integrated circuits were developed at Texas Instruments and Fairchild Semiconductor. Demand for semiconductors was, however, initially dominated by procurement for military and aerospace applications. Since the 1970s the direction of spillover has been reversed. The military market has become increasingly dependent on developments in commercial technology.

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interaction, (5) simultaneous use of two linked computers, (6) ability to devolve certain functions to remote locations without interfering with the dual processors, (7) use of display options independently of dual processors, (8) inclusion of an interrupt system, diagnostic programming, and maintenance warning techniques, and (9) associative memory development (Katz and Phillips, 1982:185). Other IBM 7090 innovations included (1) radically new parallel architecture, permitting several operations to be performed simultaneously, (2) standard modular systems component technology, (3) printed circuit cards and improved back-panel wiring, (4) an 8-bit byte, (5) greatly improved transistors and the means for manufacturing them, (6) a common mode for attaching peripherals, (7) a combination of decimal and binary arithmetic, and (8) combined fixed and variable word length operations (Katz and Phillips, 1982:189).

INVENTING THE INTERNET[10]

The Internet, to which millions of desktop computer users are connected, owes its origin to a project funded by the Defense Department Advanced Research Project Agency (ARPA). The initial objective of the ARPANET project, initiated in 1969, was to enable big computers of different design to “speak to each other." In October, 1972, at the first International Conference of Computer Communication in Washington, DC, the ARPANET project team displayed computers made by different manufactures communicating with each other at different sites across the country.

The decision to support the development of ARPANET reflected the personal interest of Joseph Licklider, who headed the ARPA Information Processing Techniques Office (IPTO) in the early 1960s, in man-machine interaction. Licklider was impatient with the "batch process" used to process data. Licklider visualized a system of "time sharing" in which a single computer located at a central location would be accessed by a number of users with individual terminals connected to the central computer by telephone lines (Hughes, 1998:261).

In 1966 Robert Taylor succeeded Licklider as IPTO head. Taylor secured the services of Lawrence Roberts, an MIT Lincoln Laboratory researcher who had already connected a Lincoln Laboratory computer to one at the RAND Corporation in Santa Monica, to head the ARPANET project to interconnect time sharing computers at seventeen academic, industrial, and government computer centers funded by ARPA. At a planning session it was suggested that if the host mainframe computers were interconnected by small interface computers, the host

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[10] In this section I draw primarily on T. P. Hughes, *Rescuing Prometheus,* New York: Random House, 1998:255-300. See also A. L. Norberg and J. E. O'Neill (with K. J. Freedman), *Transforming Computer Technology: Information Processing for the Pentagon, 1962-1968,* Baltimore, MD: Johns Hopkins University Press, 1996; and D. Saco, "Colonizing Cyberspace: National Security and the Internet," Minneapolis, MN: University of Minnesota Department of Political Science, 1996 (mimeo). For a highly personal account see K. Hafner and M. Lyon, *Where Wizards Stay Up Late: The Origins of the Internet.* New York: Simon and Schuster, 1996.

computers with different characteristics, would be able to interact through the interface computers.

The proposal was resisted by several principle investigators who wanted to develop their own software. Taylor proceeded, however, to award a contract for the development of an interface computer to Bolt, Beranek and Newman (BBN) a high-technology firm located near MIT in the Cambridge area. BBN organized a small team to design an Interface Message Processor (IMP). Both the development of the software, which would route message blocks of "packages" through alternative connections, and the engineering design problems turned out to be much more difficult than anticipated. But the "IMP guys" succeeded in completing development of the basic elements of the Internet nine months after the contract had been let.

In his assessment of the accomplishments of the "IMP guys" Thomas Hughes argued: "Future historians, fully aware of the remarkable development of the worldwide Internet, following hard upon the path-breaking ARPANET, may some day compare the inventive success of the small BBN group to the achievement of Thomas Edison and his small band of associates who invented the electric lighting system" (Hughes, 1998:278). As in the case of Edison's research at Menlo Park there was an intense dialectical interaction between advances in science and technology. Sometimes invention was informed by science and at other times invention came first followed by scientific insight.

Hughes also regards the flat management structure of the ARPANET project as an important institutional innovation. It stood in sharp contrast to the "command and control" structure employed so successfully by the military in the development of earlier air defense and ballistic missile projects. Interactions among the widely dispersed ARPANET engineers and scientists were collegial and meritocratic. Decisions were reached by consensus. Management and work styles were similar to those associated with the small start-up firms in the personal computer and software industries. Hughes also considered the ARPANET project an outstanding model of how the federal government can successfully interact with academic engineers and scientists in a mission oriented context. And he raised the rather disturbing question: If government leadership and funding is needed to sustain the revolutionary development of computing, and if public leadership and support are still needed to generate other technological revolutions in the future, where will the leadership and the funding come from (Hughes, 1998:256)?

The demonstration of the Internet at the 1972 International Conference on Computer Communication was the defining moment in the diffusion of use of the Internet. It could no longer be considered simply a potential defense application or a research tool. Although its potential capacity as a communications utility was apparent, neither the Defense Department sponsors of the research nor the members of the design team anticipated that its primary use would be for word processing personal e-mail rather than for transmitting data or research collaboration.

BIOTECHNOLOGY

Three major advances in molecular biology were essential for the transition from the old biological technology to the new biotechnology.[11]

- The *first* was the 1938 identification, by Max Delbruck at the California Institute of Technology, of DNA (deoxyribonucleic acid) as the physical carrier of genetic

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[11] For excellent and very accessible accounts see Stent (1968:390-395) and Watson (1968). For more technical accounts see Brock (1990), Cairns et al (1992), and Cohen et al (1973: 3240-3244). Stent refers to the periods in which these advances were made as the romantic phase, the dynamic phase, and the academic phase. See the Appendix for definitions of scientific and technical terms used in this chapter.

information. This was followed by the demonstration that microbes could exchange genetic information.

- The *second* was the discovery by James Watson and Francis Crick of the double helical structure of DNA in 1953. Their discovery was followed by intensive research aimed at understanding the mechanism by which DNA transferred its encoded information to the cell. Increasing numbers of biochemists and physicists were attracted to molecular genetics. Departments of immunology, virology, and microbiology were colonized by molecular biologists.
- The *third* critical breakthrough occurred in 1973 when Stanley Cohen (Stanford) and Herbert Boyer (University of California at San Francisco) and their associates demonstrated a method for stably inserting genes from a foreign organism into a host genome. The invention of the Cohen-Boyer "gene splicing" technique opened up the possibility of "engineering" the genetics of a cell to induce it to produce a specific protein that might, for example, have pharmaceutical or agronomic value.

The University - Industrial Complex

Prior to the mid-1970s almost all research in molecular biology, including the three major breakthroughs, and biotechnology had been conducted by universities and funded by foundations and the federal government. An important motivation for the very substantial growth in federal funding of research in molecular genetics was its potential contribution to solving health problems.[12] Solving health problems through biological research was more consistent with

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[12] In the fiscal year 1993, federal government support for biotechnology research amounted to approximately $90 billion. Of this $29 billion was by the National Institutes of Health (Federal Coordinating Council for Science, Engineering and Technology, 1992).

American political philosophy than a more direct attack on the social and institutional sources of ill health.

When the prospects for commercial exploitation of biotechnology became apparent, it also became obvious that the capacity to conduct the necessary research and development resided almost entirely in the universities and in a few federal laboratories. In the late 1970s and early 1980s there was a period of intense entrepreneurial activity in the formation of new university-industry relationships. The pioneers in molecular biology were thrust into a role they had not anticipated-the role of entrepreneurs in the new biotechnology industries.

Science Entrepreneurs

Many of the early genetic engineering companies were founded or co-founded by academic researchers. The commercially oriented research was initially undertaken in university laboratories. Even when the new start-up companies were able to provide their own laboratory space many entrepreneur-scientists preferred, and were permitted, to retain their university appointments.[13]

Genetic engineering as a commercial venture began in 1976 when Robert Swanson, a venture capitalist, . . . convinced Herbert Boyer, one of the inventors of the Cohen-Boyer gene splicing process, to form a company to commercialize new recombinant DNA techniques.... A new company, Genentech, was ... started on Boyer's consulting time while he was a professor at the UCSF Medical Center...In the early days Genentech did not have a laboratory so Boyer's campus laboratories were used. This was facilitated by a $200,000 grant to Boyer from

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[13] The traditional practice in universities is that faculty members are authorized to spend up to one day a week consulting. Because of the highly decentralized nature of university administration and the frequent complementary relationship between consulting activity and sponsored university research consulting activity is typically monitored rather loosely.

Genentech (Kenney, 1986:94, 95). As the biotechnology industry has matured, the role of academic researchers as entrepreneurs has receeded.

The problem faced by Genentech, and every other genetic engineering start-up company, was how to secure sufficient income during the early years to maintain its research program. Genentech attempted to solve this problem by contracting to perform research and development services for major drug companies. The first contract that Genentech entered into was to provide genetically engineered insulin producing bacteria to Eli Lilly, the leading producer of insulin. Under the contract with Lilly, Genentech was paid to conduct the research and was granted a royalty on all sales of Lilly's bacterially produced insulin. Lilly received exclusive worldwide rights to manufacture and market the insulin.

The pattern followed by Genentech was repeated many times. The potential analogy with the dramatic profits realized by early start-up firms in the computer and software industries became an almost irresistible lure for venture capitalists. Three important ingredients for starting a biotechnology firm in the late 1970s were a university scientist who had command of the knowledge and techniques, an entrepreneur with good connections in the academic and financial communities, and financial backers who could be convinced that the business would develop a successful commercial product within 5 to 7 years. It was also helpful if one or two Nobel awardees in the field of molecular genetics could be attracted to the board of the new company. It is hard to escape the conclusion that a few "delusion genes" were also important!

Industrial Organization

By the early 1980s a new pattern of relationships involving the establishment of formal institutional arrangements between universities, research institutes, and multinational pharmaceutical and chemical companies emerged. This new pattern represented an effort by large pharmaceutical companies to obtain access to capacity in the field of molecular genetics that they had neglected to develop their own laboratories. This close linkage between scientific advances and commercially useful innovations made prompt acquisition of such capacity an important source of competitive advantage. These new arrangements were sought by universities because of a perception that public funding would be much more difficult to come by than in the past. They were favored by faculty who were not unhappy to be relieved of the burden of continuous grant seeking. In these arrangements the funding corporation obtained access to not only the research skills of the principal investigator but, in some cases, to an entire laboratory or department, including assistant professors, postdoctoral researchers, and graduate students.

During the early 1980s large university-industry biotechnology research contracts were entered into by a number of major universities and research institutes and corporations. The first of these, and a model for several others, was between Massachusetts General Hospital, the primary teaching and research hospital for Harvard Medical School, and Hoechst, a German-based multinational chemical company. The details of the proposed arrangements between Hoechst and Harvard became public when Congressman Albert Gore raised questions about the propriety of "selling" the research investment, paid for by American taxpayers, to a foreign company. The final contract was rewritten to take into account some of the objections raised by Gore, particularly the coupling of federal and private funds. It is clear that Hoechst purchased more than "a window on the technology." It purchased the opportunity to build a cadre of researchers trained in a first rate laboratory in "state-of-the-art genetic engineering techniques" (Kenney, 1986:63).

A 1982 contract between Washington University (St. Louis) and Monsanto raised even more questions than the Harvard-Hoechst contract. The Washington University-Monsanto contract provided Monsanto with access to the entire Washington University Medical School. Its primary emphasis was on the development of new products with potential commercial value. The contract provided that the financial gains from the project would accrue not to the individual investigator, but rather to the institution, the particular department in the Medical School, and to the specific laboratory responsible for the creative effort.[14]

By the mid-1980s the system of industrial organization in the biotechnology industries had changed very substantially from a decade earlier, when almost all drug-related R&D had been conducted in-house by the major pharmaceutical and agrochemical companies (Arora and Garnbardella 1990; 1994). The innovation process now depended on three types of agents: the universities, small- and medium-sized biotechnology firms, and large pharmaceutical and agrochemical companies. Two factors have led to an intimate and complex set of relationships among these agents. The first is that in biotechnology the relationship between scientific advances and technical development often has been relatively direct. The second is that even the largest pharmaceutical and agrochemical firms found it difficult or excessively expensive to internalize all the resources necessary to invent and develop new biotechnologies.

The major assets of the new biotechnology firms were their close articulation with university basic research in molecular biology, their tacit know-how in applied laboratory research, and the enthusiasm and energy of their scientific entrepreneurs. The product of this research is typically highly specific-a new protein obtained from a genetically engineered organism, for example. The synthesis of a new protein, however, does not complete the process. Engineering know-how is required to scale up from the laboratory bench to manufacturing.

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[14] In view of the intensive involvement of the private sector pharmaceutical and biotechnology companies in university research since the early 1980's it is somewhat difficult to understand the controversy that greeted the 1999 announcement of a collaborative relationship between Novartus and the University of California-Berkeley. My own interpretation is that it reflects an increased sensitivity around the issue of the private control of public resources (Rausser 1999).

Familiarity with clinical testing procedures and with the regulatory process is also essential. Finally, an extensive distribution network is necessary to successfully bring new products to the market. These are capacities that universities and new biotechnology firms did not have and that are very costly to acquire. Cooperative relations between universities, the new biotechnology firms, and the larger pharmaceutical and agrochemical firms proved to be advantageous for the development and commercialization of new biotechnology products.

ELECTRIC LIGHT AND POWER

The electric light and power industry represents a partial qualification to my generalization in that government has played an important role in technology development and transfer in almost every industry that has become competitive on a global scale. The initial role of the public sector was in the area of institutional innovation, in what came to be termed the Insull System. The role of the public sector in the development of atomic power after World War II has provided important fuel to the critics of the involvement of the public sector in technology development (Cohen and Noll 1991).

The First American Industrial Laboratory[15]

The inventions that lead to electric power technology were supported entirely by the private sector. But the development of electrical technology drew substantially on prior scientific research. "The lexicon of electricity—ohms, amperes, galvanometers, hertz, volts—is a gallery

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[15] Adapted primarily from Thomas P. Hughes, " The Electrification of America: The System Builders," *Technology and Culture* 20(1979): 124-161; Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930*, Baltimore: The Johns Hopkins University Press, 1983; Leonard S. Reich, *The Making of Industrial Research: Science and Business and GE and Bell, 1876-1926*, Cambridge, MA: Cambridge University Press, 1985. I have also drawn on the revisionist biography by David E. Nye, *The Invented Self: An Autobiography from Documents of Thomas Edison*, Odense: Odense University Press, 1983; and the popular account by Neil Baldwin, *Edison: Inventing the Century*, New York: Hyperion, 1995.

of great scientists of the eighteenth and nineteenth centuries (Ausubel and Marchetti, 1977: 111). The first American industrial research laboratory in the modern sense was established by Thomas A. Edison at Menlo Park, New Jersey in 1876. The invention of the high-resistance incandescent lamp and the development of a system for the generation and distribution of electric power by Edison and his research team at Menlo Park established the foundation for the electric utility industry.

Prior to establishing his Menlo Park laboratory Edison had been responsible for a number of important inventions, the most important being in the area of telegraphy. In the early 1870s Edison established a factory in Newark, New Jersey to manufacture telegraphic equipment for Western Union. At Newark Edison began to assemble the research and development team that would become the core group for his Menlo Park laboratory (Reich, 1985: 42-45). He visualized the Menlo Park facility as an "invention factory"—capable of turning out "a minor invention every ten days and a big thing every six months or so." He chose the Menlo Park location because it would provide insulation from the distractions of the Newark urban environment. Edison was a compulsive worker who often worked and slept in his laboratory for several days at a time, and he expected the same dedication from his staff.

The staff that Edison attracted to Menlo Park included Charles Batchelor, a master craftsman, who had come from England to install textile machinery and had joined Edison in Newark; John Kreusi, trained in Switzerland as a master mechanic, who transferred from Newark to take charge of the Menlo Park machine shop; Hermon Claudius, who had a Ph.D. degree in electrical engineering and experience as a system designer in the Austria telegraph system; and Francis Upton, a Princeton graduate who had spent a postgraduate year studying the mathematics of electrodynamics with Herman von Helmholtz at the University of Berlin. The

Menlo Park laboratory complex also involved by a broad array of expensive machine tools, chemical apparatuses, library resources, scientific instruments, and electrical equipment to support the inventive efforts of the staff.

In 1878, 2 years after moving to Menlo Park, Edison began to focus his efforts on the development and introduction of a system of electric lighting. On October 20, 1878 he announced in the *New York Sun* a plan for underground distribution of electricity form centrally located generators. At the time of his announcement Edison had no generator, no promising incandescent lamp, and no system of distribution. A major problem that had to be solved was the invention and development of a high-resistance filament for the incandescent light. On the basis of careful economic calculations Edison determined that a high-resistance lamp filament, in contrast to the low-resistance one tried by earlier inventors of incandescent lamps, should be necessary to compete economically with gas lights.

These calculations did not, however, lead directly to a selection of an appropriate filament. Edison and his assistants found it necessary to test over 3000 different materials, including platinum and bamboo, before finally settling on carbonized cotton thread, Hughes, notes that “Edison’s method of inventions and development in the case of the electric light system was a blend of economics, technology (especially experimentation), and science. In his notebooks pages of economic calculations are mixed with pages reporting experimental data . . . and hypothesis formulation based on science” (Hughes, 1979: 135). In October 1879, the same month in which he identified the first practical filament, Edison announced the generator for his system. The Pearl Street central station began to supply light for the Wall Street district in September 1882. The age of central-station incandescent lighting had begun. The firm started by Edison later merged into the Edison General Electric Company (later to become the General Electric Company).

Institutional Innovation

The initial role of the public sector in the electric power and light industry involved the development of an integrated, technically efficient, monopolistic and publicly regulated system of delivering electric power. This system, known as the Insull System, was first achieved in Chicago. Samuel Insull had served his apprenticeship with Edison at Melno Park and at the Edison General Electric Company in Schenectady.

At the age of 32 Insull moved to Chicago to become president of the Chicago Edison Company. The system that Insull created in Chicago became a model for the public utility industry. The development of a publicly regulated system capable of providing a dependable supply of electric power at acceptable prices to consumers and reasonable returns to inventors required the mobilization of substantial political resources. Methods were found by which politicians “obtained wealth from political power without having to steal public money” (Hughes, 1983: 206).

The result was an implicit social contract in which the utilities undertook to provide reliable and affordable electricity in exchange for a socially determined rate of return. This system remained intact until the 1970’s when it was confronted by a maturing technology, raising costs of primary energy, and the emergence of an aggressive environmental movement (Hirsh and Serchuk, 1996). The effect of the Energy Policy Act of 1992, designed to encourage competition and deregulation in the electrical utility industry, induced the deconstruction of the integrated system that Samuel Insull and other leaders of the electric power industry had enacted in the 1920's.

Premature Commercialization of Nuclear Power[16]

In the period immediately after World War II it was anticipated that nuclear energy would largely replace fossil fuels as the primary fuel source in the generation of electricity. The prospect of developing a peaceful use for nuclear energy generated considerable enthusiasm in both the scientific community and the general public. It was asserted that nuclear energy would make electricity so inexpensive that it would be "too cheap to meter" (Pool, 1997: 71).

The United States Atomic Energy Commission (AEC), established by the Atomic Energy Act of 1946, was given the authority to promote and regulate the development of nuclear technology for both military and nonmilitary purposes. In 1951 the AEC set out to test a number of reactor designs for nuclear power plants. However, President Eisenhower's "atoms for peace" program launched in 1954 resulted in a more intensive and less deliberative effort to develop a civilian nuclear power program.[17] The Atomic Energy Act of 1954 provided a statutory basis for the private sector development of nuclear power and for cooperation in the development of "peaceful uses" of nuclear technology with other countries (Hewlett and Hall, 1989).

Enrico Fermi demonstrated the feasibility of controlled nuclear fission at the University of Chicago's Stag Field laboratories on December 2, 1942. A decade and a half later the first commercial nuclear reactors (at Calder Hill in the United Kingdom in 1956, and at Shipping Port

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[16] This section draws heavily on Cowan (1990), MacKerron (1994), World Energy Council (1993), Hill et al. (1995), Tester et al. (1991), and Pool (1997).

[17] The Eisenhower speech in December 1953 was a response to progress in the development of the nuclear powered submarine under the direction of Hyman Rickover, who headed the Naval Reactors Branch of the AEC. In this effort Rickover brought together the design for a pressurized water reactor, developed under the direction of Alvin Weinberg at the Oak Ridge AEC Laboratory, with engineering capacity from the Westinghouse Corporation (Marcus, 1992:104).

New York in 1957) came on line. It took another 30 years for nuclear reactors to account for 20% of electricity generated in the United States. In the United States, the earliest nuclear plants developed to produce electricity were reactors designed for use in submarines. In the United States, and later in Germany and Japan, large public R&D programs were complemented by substantial private research investment by firms such as Westinghouse, General Electric, Babcox and Wilcox, Siemens, AEG, and Mitsubishi. In the United Kingdom, France, and the U.S.S.R., the research was conducted almost exclusively by the public sector. Nowhere were the electric utility firms heavily involved in nuclear research. They assumed that replacing a fossil fuel-fired boiler with a nuclear reactor to produce steam would be a relatively simple process-"a nuclear reactor was just another way to boil water."[18]

The anticipated economies of scale and cost reductions from "learning by doing" and "learning by using" were not realized, however. They were more than offset by increases in the complexity of reactors, due partly to initial design errors, but largely to increasingly stringent safety standards. In many cases, final costs exceeded initial estimates by 100%.[19] It became apparent by the mid-1970s that the simple and comparatively inexpensive light-water reactors of the late 1960s were, partly on engineering grounds and partly due to safety concerns, no longer commercially viable (MacKerron, 1992).

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[18] A number of different reactor designs were advanced in the 1950's and 1960's. "Nuclear reactors are classified by, two of the materials used in their construction: the coolant used to transfer heat from the reactor core; and the moderator used to control the energy level of the neutrons in the reactor core. In a light water reactor both coolant and moderator are light water-H20. In a heavy water reactor both are heavy water (D_2O). In a graphite reactor the coolant is a gas, usually helium or carbon dioxide, and the moderator is graphite" (Cowan, 1990:545). Light water reactors advanced along a politically determined ??? and by the time other technologies were ready to compete it was too late (Arthur, 1990: 541-67; Cowan, 1990: 541-67). In retrospect the "path dependence" was forced by strategic rather than economic considerations. Pool argues that without an atomic weapons program no country would have built uranium-enrichment facilities: “without the enriched uranium supplied by the post-war bomb building program, it is unlikely that the light water reactor would have been a serious contender much less the design of choice" (Pool, 1997: 43).

[19] A rapid surge in new construction of nuclear plants in the 1960s has sometimes been interpreted as induced by the 1973 oil price shock. Damian (1992:600) argues, however, that the difficulties encountered by nuclear power were at least partially responsible for the timing of the oil price shocks of 1973 and 1978.

Beginning in the 1970s, safety requirements for nuclear power plants in the United States have been continually tightened by the Nuclear Regulatory Commission (successor to the Atomic Energy Commission) in response to public risk perception. Although it is not clear that changes in these requirements resulted in substantial safety improvements, the frequent design changes in the course of construction did result in substantially higher construction costs. During the 1980s, average construction time in the United States rose to over 10 years. The costs of new nuclear plants of comparable size, corrected for inflation, quadrupled in little more than a decade. These higher capital costs pushed the cost of producing electricity from nuclear-fueled plants even higher relative to coal-burning plants. As electrical shortages began to emerge in the 1980s, utilities increasingly turned to natural gas as a source of primary energy because plants could be brought on line relatively quickly, even though cost per kilowatt hour might be higher than for either nuclear power or coal.

A Faustian Bargain?

In an important paper published in 1972 Alvin M. Weinberg, a leading atomic scientist and director of the Oak Ridge National Laboratory, anticipated many of the problems that have constrained the development of the nuclear power industry. 'We nuclear people have made a Faustian bargain with society. On the one hand we offer the catalytic nuclear burner-an inexhaustible source of energy. Even in the short range, when we use ordinary reactors, we offer energy that is cheaper than fossil fuel. Moreover, this source of fuel, when properly handled, is almost nonpolluting. But the price we demand of society for this manageable energy source is both a vigilance and a longevity in our social institutions that we are quite unaccustomed to" (Weinberg, 1972:33).

Weinberg went on to emphasize that the problems of reactor safety, transport of radioactive materials, and disposal of fuel rods and other high-level radioactive waste could be managed only by the commitment of an exceptional level of technical and scientific competence. He advocated that nuclear power production and waste storage be located at a limited number of sites where the technical and scientific skills and the social arrangements necessary for the management of a nuclear industry could be ensured. Society has not yet demonstrated a willingness to pay the price of Weinberg's Faustian bargain.

In the United States no new plants have been ordered since 1978 and energy plants ordered after 1974 were canceled. The path followed by France has been quite different.[20] At the time of the first oil crisis in 1973, imported oil accounted for over two-thirds of French energy consumption. Following the oil embargo, the French government committed itself to the construction of six 900-MW reactors per year. The rationale for the program was that nuclear energy was the only form of power that could be developed based on French resources. The French developed capabilities in all areas of the nuclear power cycle, from reactor design and construction to fuel supplies and waste treatment.

Renewable Energy

If renewable sources of primary energy are to become widely adopted over the next quarter century, it seems clear that sustained public support will be required (Grubb, 1993; World Energy Council, 1994:48-52) (Table 13.1). The limited commercial success that renewable sources such as biomass, wind, solar-thermal, and photovoltaic have achieved has largely been due to the limited public support for research and development of these technologies and to

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[20] This and the next paragraph draw heavily on Marcus (1993: 394-395).

changes in regulatory regimes. At present, photovoltaics appear to have the greatest potential for commercial viability.

A number of potential benefits not captured by conventional project investment criteria have been advanced in favor of renewable energy sources. These include (1) reduced air pollution, (2) abatement of global warming, (3) diversity of fuel supply, (4) reduction in the risks of nuclear proliferation, (5) restoration of degraded lands, and (6) contribution to decentralized regional development (Johansson et al., 1993:4). If electricity based on renewable resources is preferred because of these environmental and related benefits, the policy interventions required will include (1) reduction or removal of subsidies to artificially lower the costs of fossil and nuclear fuels, (2) design of policy instruments that ensure that environmental and other external costs are more adequately reflected in energy prices, and (3) stronger public support for research and demonstration of renewable energy technologies. As of the late 1990s support for such policy intervention in most major industrial countries had declined compared to a decade earlier (Dooley, 1998).

SOME LESSONS

- Two decades ago Nelson and Langolis identified three types of public support that have been successful (Nelson and Langolis, 1983: 814-818). One is direct support of technology development in areas in which the government is strongly involved. A dramatic recent example is the Internet, which was initially developed by the Defense Department's Advanced Research Projects Agency (ARPA) to facilitate communication among its contractors and grantees. A second area in which government has been successful is in support for the development of generic technology. A recent example has been the support for basic research in molecular biology and closely related research in biotechnology. A third category has been in the area of client-oriented technology. Agricultural research is a highly successful example. Most of the increases in plant and animal productivity of the last century have been the result of public sector agricultural research. An important element in the success of client-oriented public research is the close articulation between the public sector suppliers and the private sector users of knowledge and technology. The generalizations that emerged from the Nelson-Langlois analysis of almost two decades ago retain much of their currency. But there are also some additional lessons.

- A second lesson that emerges from U.S. experience is the importance of a decentralized national research system. The structure of the U.S. national research system took its present form in the half century between 1880 and 1930. This period witnessed the formation of scientific and technical bureaus within the federal government, the establishment of industrial research laboratories, the formation and growth of public and private research universities, and the emergence of philanthropic foundations to support research and education. These institutions drew on each other for their entrepreneurship and leadership. This decentralized structure has given the United States greater capacity to adjust to changing national and global priorities, and to direct research to the exploration of commercial opportunities, than in countries in which government-funded research is conducted primarily in national laboratories or research institutes only marginally linked with universities and in which private sector research is limited primarily to large firms (Mowery and Rosenberg, 1998:11-46).

- The case of atomic energy represents an important example of the premature forcing, by the political system, of a science based technical change. It is possible that future changes in energy resource endowments and environmental concerns will induce the scientific and technical effort necessary to generate an economically viable and environmentally benign nuclear energy technology. But, at least in retrospect, it is difficult to argue that the time when this will occur has been advanced by premature forcing of alternative development. It will come only as a result of very large public fording of technology development. The economic viability of alternative energy sources, particularly photovoltaic, has probably been delayed by environmental public funding.
- The rate of technology development is not enhanced by superficial notions of the relationship between advance in scientific and technical knowledge nor will it be advanced by the failure of the scientific community to face up to the problem of the allocation of public research resources and its commitment to peer review as the only way to assure good science (Fig. 1). The science community has consistently been unwilling to confront the issue of criteria for the allocation of public resources to research. The best the Press Committee (1995) could come up with is that "The President and Congress should ensure that the Federal S & T budget is sufficient to allow the United States to achieve preeminence on a select number of fields and to perform at a world-class level in other major fields." At a time when the linkages between advances in scientific knowledge and technology development are best described in terms of an "interactive model" and when the implicit social contract between science and society has severely eroded this is not good enough.

- I have been forced, as I prepared for the presentation of this seminar, to reassess the role that military R & D has played in advancing technology for civilian use. Examples range from (a) New England armory practice; (b) development of the computer to;
  (c) development of the Internet. This is the subject for a paper that I have not yet started writing.

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The Linear Model

The Quadrant Model

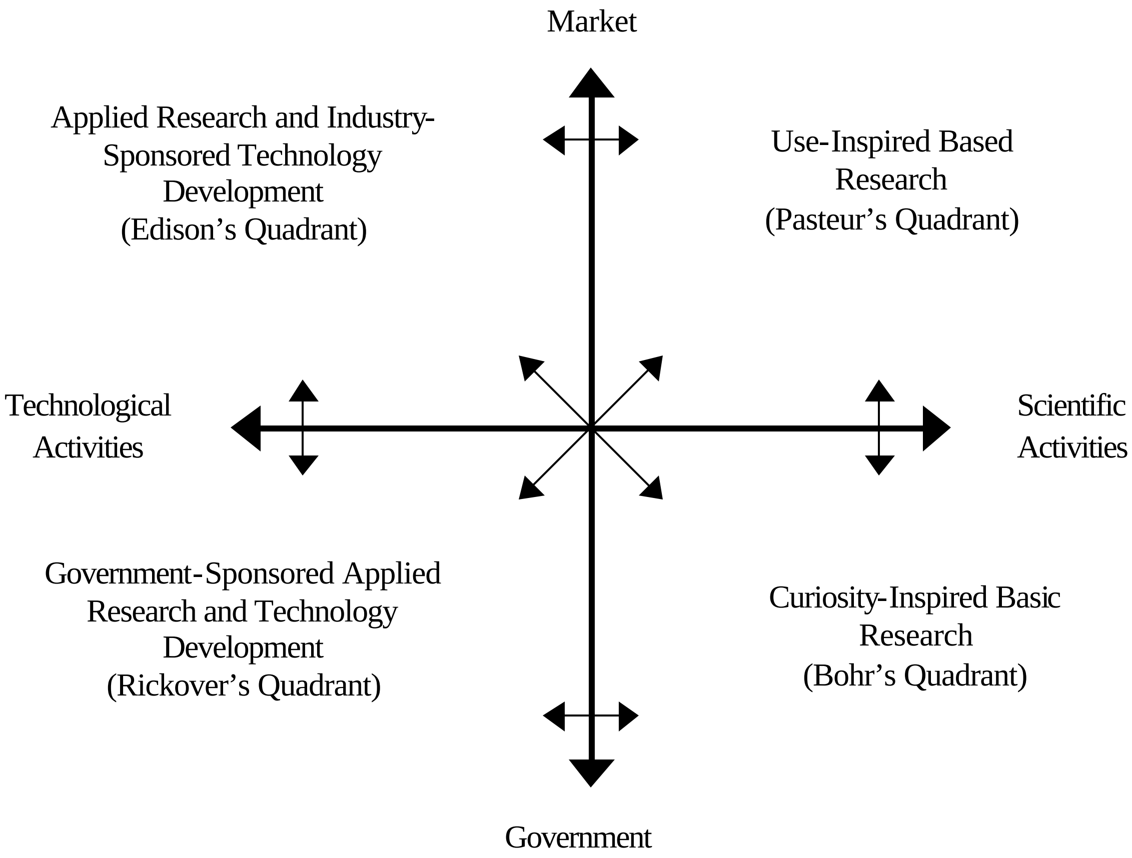

Figure 1: The Linear and Quadrant model of organization of scientific research and technology development. (Source: Adapted from Vernon W. Ruttan, *Technology, Growth, and Development: And Induced Innovation Perspective*, New York: Oxford University Press, 2001.)